# APPENDIX C

# DESIGN LEVEL GROUNDWATER FLOW AND OXYGEN INTRUSION MODELING

**Prepared By:**
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## C-1 BACKGROUND

The groundwater flow system at the Holly Street Landfill Site consists of a shallow unconfined aquifer within the refuse and underlying Recent Alluvial sediment as discussed in Section 4.5 of the RI/FS report (Anchor et al, 2001). Groundwater flow within this unconfined aquifer is generally directed from the upland areas toward Whatcom Creek. Fine-grained silts and clays present beneath the aquifer function as confining layers, restricting downward groundwater flow into deeper units.

Leachate within the refuse is generated from infiltration of incident precipitation and from lateral inflow of groundwater into the landfill area. Tidal influence creates a sinusoidal groundwater flow path as the groundwater approaches the point of discharge into Whatcom Creek, and oscillates in response to tidally propagated waves. These oscillations are most pronounced within approximately 20 feet of the shoreline.

Monitoring performed during the RI/FS (Anchor and Aspect 2001) indicated that copper and zinc concentrations exceed MTCA surface water cleanup levels in shoreline seeps along portions of the northwest lobe of the Holly Street Landfill. The geochemical data suggest that water within the Whatcom Creek estuary, high in dissolved oxygen, migrates into the shallow groundwater zone during high tides, creating oxidizing conditions within the saturated refuse. As discussed in the RI/FS, oxidizing conditions are expected to mobilize copper and zinc present within the refuse.

The cleanup alternative selected by Ecology in the CAP includes removal of a portion of the refuse currently exposed to oxygenated water infiltrating from Whatcom Creek and placement of a permeable shoreline cap. The intent of this action is to reduce concentrations of copper and zinc discharging to Whatcom Creek by displacing the zone of mixing outward from the refuse. Such displacement would separate the reduced geochemical environment within the refuse from oxidizing surface water, which in turn would reduce the release of dissolved copper and zinc.

## C.2 PREVIOUS ANALYSIS

Section 8.1 of the RI/FS describes preliminary numerical modeling analysis of the potential effectiveness of the action in reducing copper and zinc discharges to Whatcom Creek. For that analysis, a two-dimensional groundwater flow model was constructed using the U.S.G.S. MODFLOW model (MacDonald and Harbaugh 1988). The model used a simplified geometry to represent the shoreline cap configuration. The analysis evaluated the influence of tidal fluctuations on advective transport of a non-sorbing tracer to assess the effectiveness of the cap design in reducing intrusion of oxygenated water from Whatcom Creek into the refuse. The preliminary results indicated that a non-sorbing constituent (e.g., dissolved oxygen) would be attenuated within a 5-foot thick soil cap with permeability on the order of $10^{-2}$ centimeters per second (cm/sec).

The performance of the cap in the preliminary model used in the RI/FS was sensitive to the permeability of the cap, with values greater than $10^{-2}$ cm/sec being less effective at reducing oxygenated water intrusion. However, the preliminary model did not consider diffusion and dispersion process that also influence transport of a non-sorbing constituent. Data collected during the March/April 2002 tidal monitoring study at the Site indicated that tidal mixing and dispersion could be a significant factor in enhancing the mobility of dissolved constituents and dissolved oxygen (see Appendix B.2). Consequently, additional refined numerical modeling analysis was completed to support the shoreline cap design for the Design-Level Report.

## C.3 DESIGN-LEVEL MODELING ANALYSIS

For the Design-Level modeling analysis, a numerical transport analysis was performed to evaluate the influence of tidal fluctuations, molecular diffusion, and hydrodynamic dispersion on inland migration of a non-sorbing tracer to finalize the design criteria for the shoreline cap.

The scope of the Design-Level modeling analysis included:

- Revising the RI/FS model grid to better represent hydrostratigraphic units and physical characteristics of the site
- Calibrating the revised groundwater flow model to data from an additional tidal monitoring study conducted at the site in March/April 2002
- Running a numerical transport model to assess migration of a non-sorbing constituent, nominally dissolved oxygen, into the landfill through a 5-foot engineered cap considering both advection and dispersion.

### C.3.1 Groundwater Flow Modeling

A numerical groundwater flow model was developed to provide groundwater velocity values for input into a numerical groundwater transport model. Sections below describe model development and calibration.

#### *C.3.1.1 Model Development*

For this analysis the MODFLOW model grid developed for the RI/FS was modified to reflect the sloping contact between the Recent Alluvium and the underlying Bellingham Drift. Previously the modeled hydrostratigraphic units were represented as a sequence of horizontal layers (RI/FS Report; Figure 8-1). The finite-difference grid and the model layering used to represent hydrostratigraphic units encountered at the site are illustrated on Figure C-1. The grid is comprised of one row, 64 columns, and seven layers. The model grid consists of two principal hydrostratigraphic units, refuse and alluvium. Based on a review of the boring logs, the alluvium was further divided into an upper more permeable sandy unit and a lower less permeable silty unit. The fine-grained glacial marine deposits of the Bellingham Drift underlying the Recent Alluvium had negligible contribution to groundwater flow discharging to Whatcom Creek and were not represented in the model.

Precipitation recharge and groundwater flow into the model grid from the north (upgradient) was represented by specifying a constant groundwater elevation (head) of 11 feet in model cells along the right edge of the model grid (see Figure C-1a). Tidally fluctuating groundwater discharge to and recharge from Whatcom Creek was represented using time-varying specified head cells on the left side of the model grid. One column of cells contacting the creek and one layer of cells underlying the creek (Figure C-1a) were assigned head values based on tidal stage recorded by the National Oceanographic and Atmospheric Administration (NOAA) tide gauge located at Cherry Point, Washington. For the calibration effort, a regular sinosoidally varying portion of the tide stage recorded on hourly intervals between April 16 and 17, 2002, was replicated to specify the head of cells adjacent to Whatcom Creek for a 14-day simulation. Because the lowest tide observed during the monitoring study (0 ft MLLW) fell below the base of the refuse horizon at +7 ft MLLW, it was not practical to specify constant head cells in the model layers representing the refuse horizon. Therefore columns of cells with very high hydraulic conductivity (K) were specified in the region of the model occupied by Whatcom Creek to facilitate surface water contact with the refuse horizon at high tides.

Within the model grid, the uppermost active layer is treated as an unconfined layer while lower layers can be treated as confined/unconfined. This is accomplished through the "LAYCON" variable in MODFLOW. The storage parameter in the lower layers and in cells adjacent to Whatcom Creek were automatically adjusted in the model to use a storage coefficient (Ss) when the cells were fully saturated or a specific yield value (Sy) when the water table dropped below the top of cells. For these simulations, portions of the refuse and Alluvium adjacent to Whatcom Creek became unsaturated during low tides and rewetted during high tides. The REWET option was specified to simulate this behavior in model cells adjacent to Whatcom Creek.

### *C.3.1.2 Calibration*

The groundwater flow model was calibrated using a combination of manual and automated parameter estimation techniques. Initially, hydraulic conductivity (K) and storage parameters from the calibrated RI groundwater model were used. The hydraulic parameters were then manually adjusted in an iterative process until good agreement was obtained between modeled and observed groundwater elevation at wells MW-2 and MW-3. Final calibration was performed using an automated parameter estimation program, PEST (Watermark Computing, 1994). Final calibrated hydraulic parameters are listed in Table C-1. Good agreement between modeled and observed groundwater elevations in wells MW-2 and MW-3 was obtained with the calibrated model (Figure C-2).

**Table C-1**
**Calibrated Model Hydraulic Parameter Summary**

| Hydrostratigraphic Unit | K, cm/sec | Ss, 1/ft | Sy | n |
|---|---|---|---|---|
| Refuse | .04 | 5e-5 | .122 | .25 |
| Upper Alluvium | .003 | 5e-5 | .033 | .2 |
| Lower Alluvium | .0003 | 1.5e-5 | .045 | .2 |
| High K Boundary Cells | 100 | 0.001 | .01 | .9 |

The most significant change in model parameters compared to the preliminary modeling effort described in the RI/FS is the representation of the Recent Alluvium with an upper and lower unit. Previously, the Recent Alluvium was represented as a single hydrostratigraphic unit with a uniform hydraulic conductivity of 0.00031 cm/sec. For the Design Level analysis, the hydraulic conductivity of the lower alluvium was unchanged from the value used in the RI/FS. The hydraulic conductivity of the upper alluvium in the Design Level was an order of magnitude higher at 0.003 cm/sec. This change better reflects the loose sandy materials encountered below the refuse horizon in boring MW-3.

## C.3.2 Contaminant Transport Modeling

Numerical transport modeling was performed to assess the influence of cap hydraulic conductivity and thickness on attenuation of dissolved oxygen intrusion in surface water from Whatcom Creek. Sections below describe model development, simulations to assess cap performance, and results.

### *C.3.2.1 Model Development*

To represent the shoreline cap in the numerical model, the hydraulic conductivity of model grid cells near Whatcom Creek were modified as illustrated in Figure C-3. The modifications consisted of changing the hydraulic conductivity of cells in the uppermost two model layers within 30 feet of Whatcom Creek. To represent the shoreline cap, the hydraulic conductivity of three cells in the uppermost layer between 25 and 30 feet from

Whatcom Creek and all cells in the second (5 foot thick) layer were set to an initial value of 0.02 cm/sec. Cells in the uppermost layer to a distance of 25 feet from Whatcom Creek were set to the high K value of 100 cm/sec to simulate surface water flow over the engineered cap during high tides.

The numerical transport model was developed using MT3D (Zheng, 1990). For this, porosity values of 0.25 and 0.2 were assigned to the refuse and Alluvium units, respectively, based on data presented in the RI report. A uniform dispersion coefficient of 1 foot and aqueous diffusion coefficient of 2 x $10^{-5}$ $ft^2$/day were used in all model layers. Because oxygen is not expected to adsorb to soil materials, transport was simulated without retardation. Cap performance was evaluated by specifying a constant concentration boundary at a unit value in cells representing Whatcom Creek (Figure C-3).

#### *C.3.2.2 Cap Performance Simulations*

Two cap design scenarios were evaluated: a cap with a uniform hydraulic conductivity of 0.02 cm/sec (the same as specified for the RI/FS) and a cap with a uniform hydraulic conductivity of 0.005 cm/sec. Multi-year transport simulations were performed with both configurations until a steady-state concentration profile was developed. The steady-state concentration profile for the 0.02 cm/sec cap and the 0.005 cm/sec cap were similar. The concentration profile for the 0.02 cm/sec cap simulation is presented on Figure C-4.

### C.3.3 Results

As shown in Figure C-5, the modeling analyses indicate that a 3-foot-thick shoreline cap constructed at a permeability of approximately 0.02 cm/sec would attenuate migration of a non-sorbing constituent to less than 5 percent of the concentration of that constituent in Whatcom Creek while the cap with a lower hydraulic conductivity of 0.005 cm/sec attenuates the influx from Whatcom Creek by more than 99 percent. Groundwater migrating towards Whatcom Creek through the refuse horizon will also experience a substantial biological and chemical oxygen demand as a result of contact with materials placed in the landfill. This oxygen demand would further reduce the dissolved oxygen concentration in groundwater contacting the refuse. Currently, Whatcom Creek is a relatively significant source of oxygenated water within the zone influenced by tidal fluctuations. The modeling results are significant in that they indicate that a 3- to 5-foot thick layer of soil with a hydraulic conductivity of 0.02 cm/sec or less will greatly reduce the oxygen flux inland from Whatcom Creek. With this source of oxygen cut off, the oxygen concentration in groundwater within the refuse will decrease substantially following placement of the cap. Consequently, concentrations of zinc and copper in groundwater within the refuse will also decrease because both metals are less soluble at lower dissolved oxygen concentrations. As a result of the reduction in oxygen influx to the refuse, and mixing and dispersion within the cap as a result of tidal fluctuations, the copper and zinc concentrations in groundwater discharging to Whatcom Creek will be substantially reduced following placement of the shoreline cap.

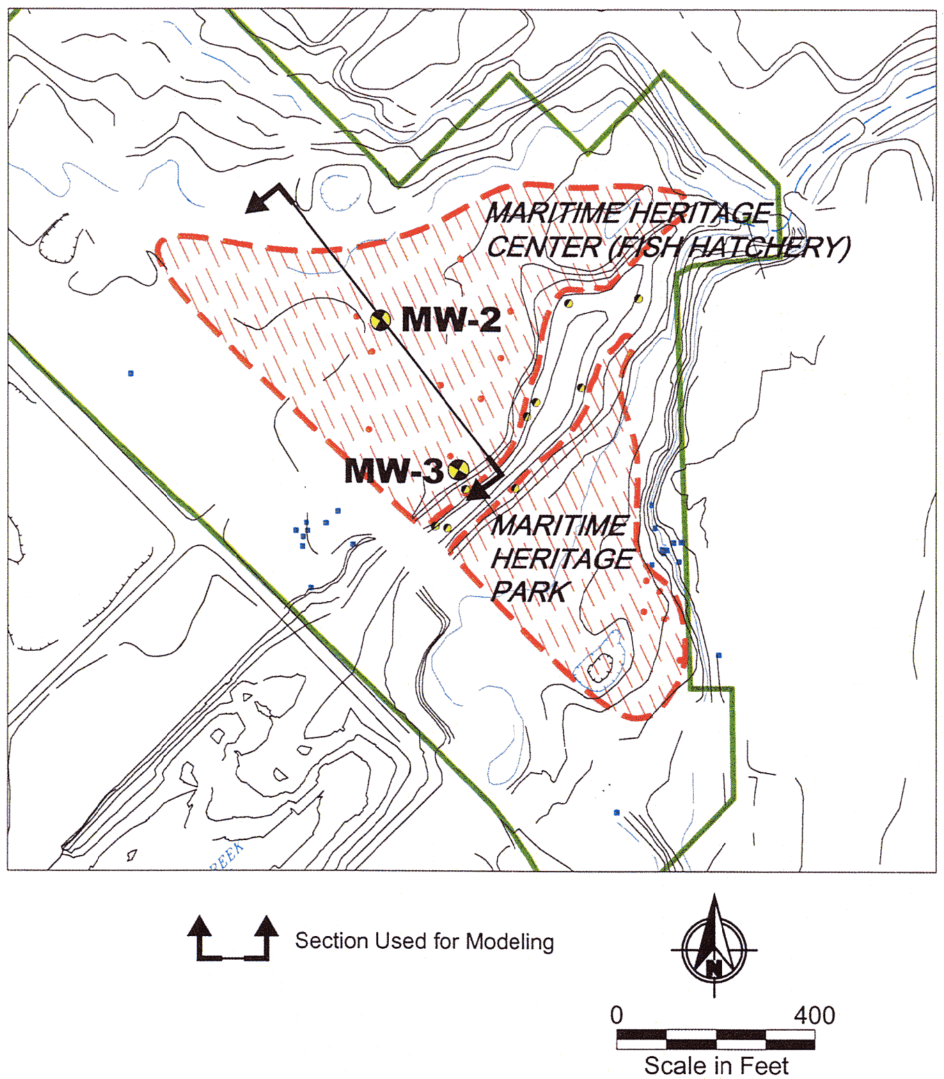
## C.4 REFERENCES

Anchor Environmental, LLC, Aspect Consulting, LLC, and Heartland, 2001, Remedial Investigation/Feasibility Study Holly Street Landfill Redevelopment Project, Draft Final, November 2001, Prepared for City of Bellingham

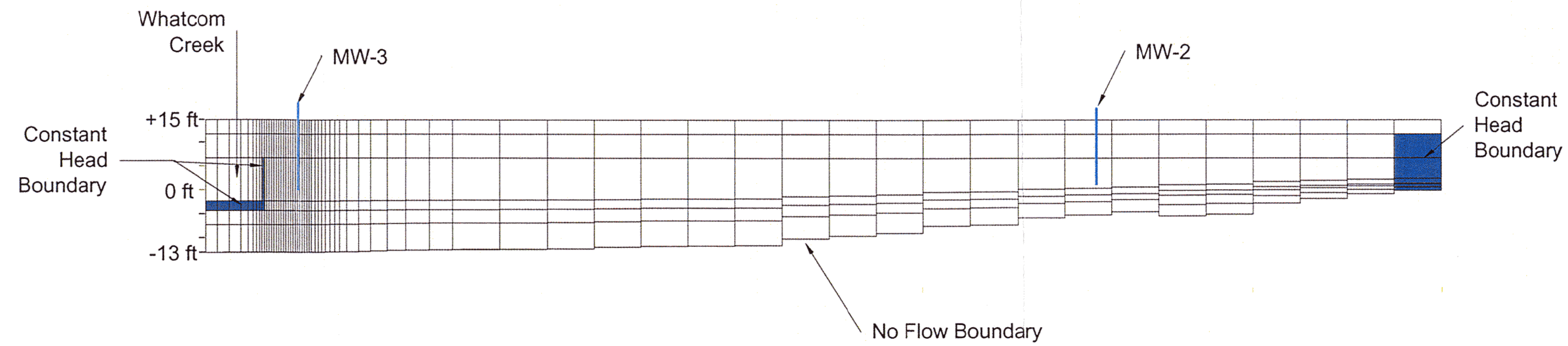
McDonald, M.G. and A.W. Harbaugh, 1988, *A Modular Three-Dimensional Finite-Difference Groundwater Flow Model*, U.S. Geological Survey Open File Report 83-875.

Zheng, C., 1990, MT3D: A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems, Report to the U.S. Environmental Protection Agency, Ada, OK, 170 pp.

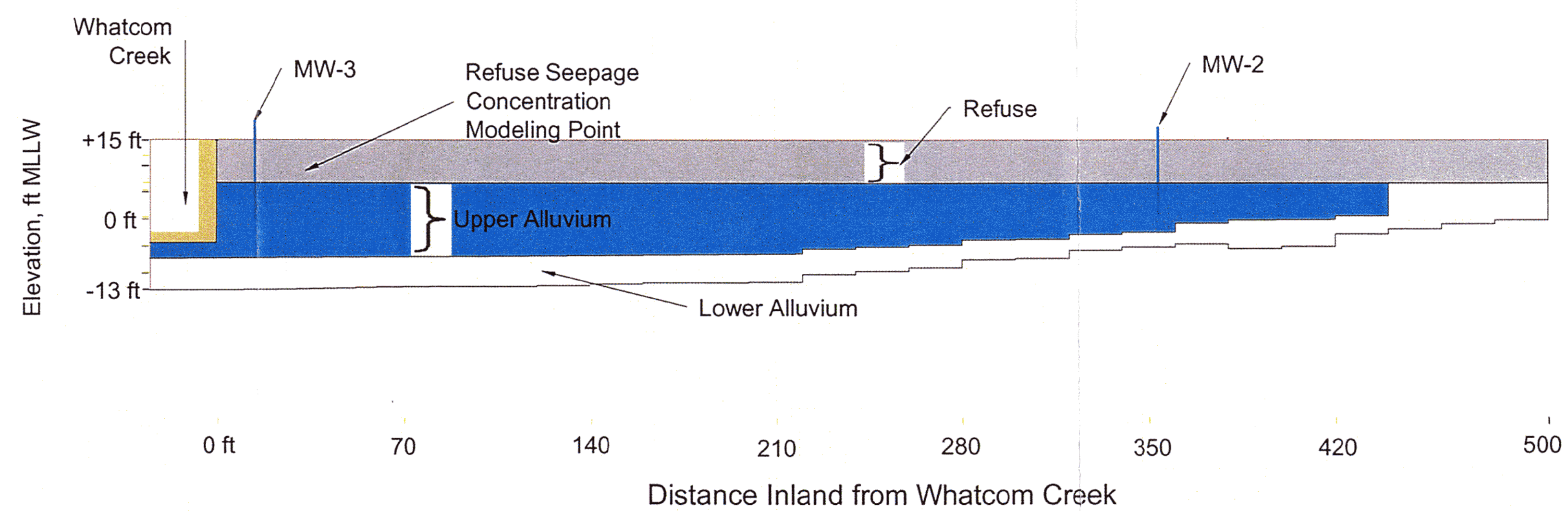
## Well Location Map




## C-1a - Calibration Model Grid with Boundary Conditions




## C-1b - Hydrogeologic Unit Representation




Hydraulic Conductivity, cm/s

- 0.003
- 100
- 0.04
- 0.0003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**Model Layout for Calibration**

Holly Street Landfill
Bellingham, Washington

| | |
|---|---|
| DATE: | 10/03/02 |
| DESIGNED BY: | DWM |
| DRAWN BY: | MS |
| REVISED BY: | |
| PROJECT NO. | 990139 |
| FIGURE NO. | C-1 |

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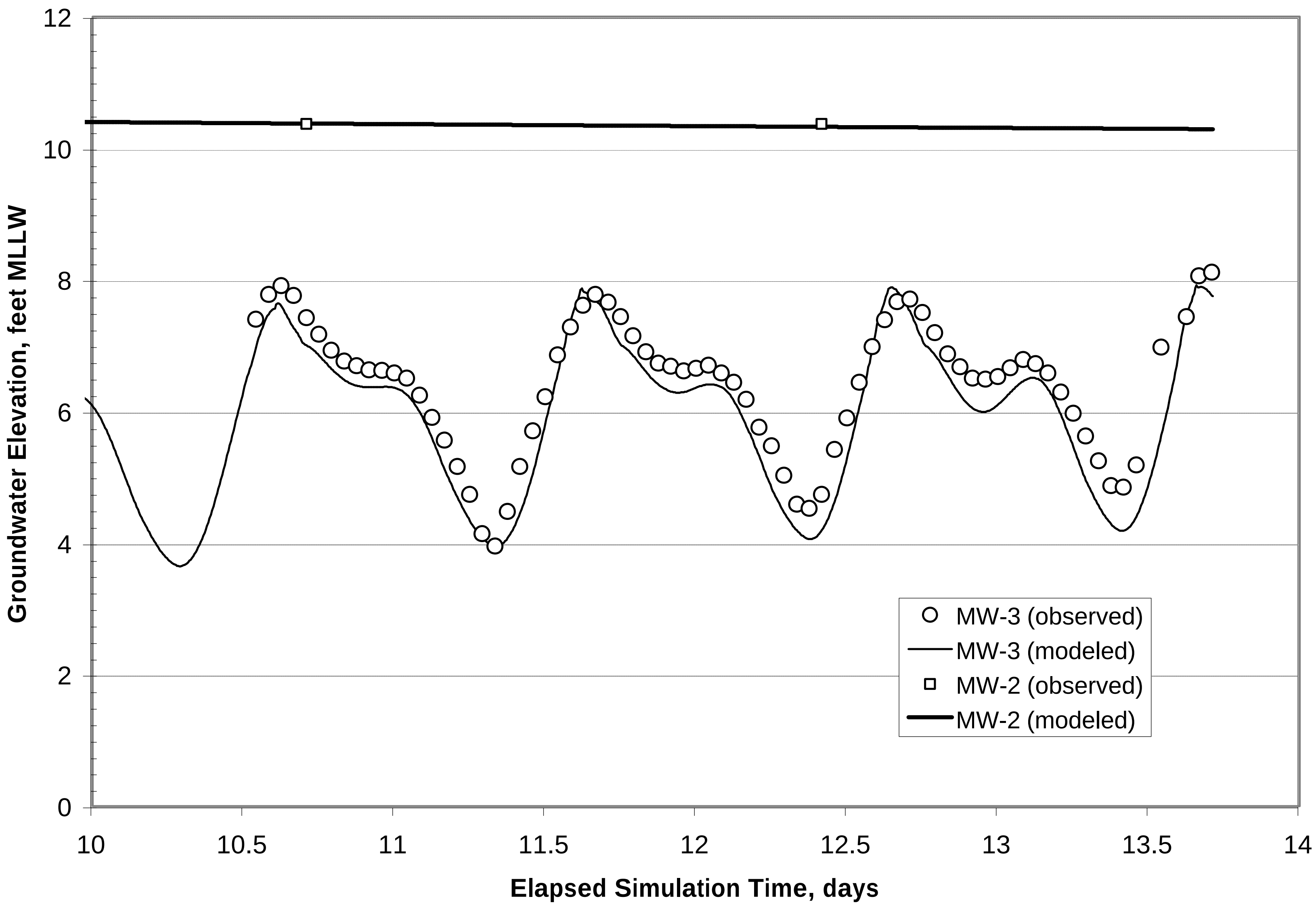


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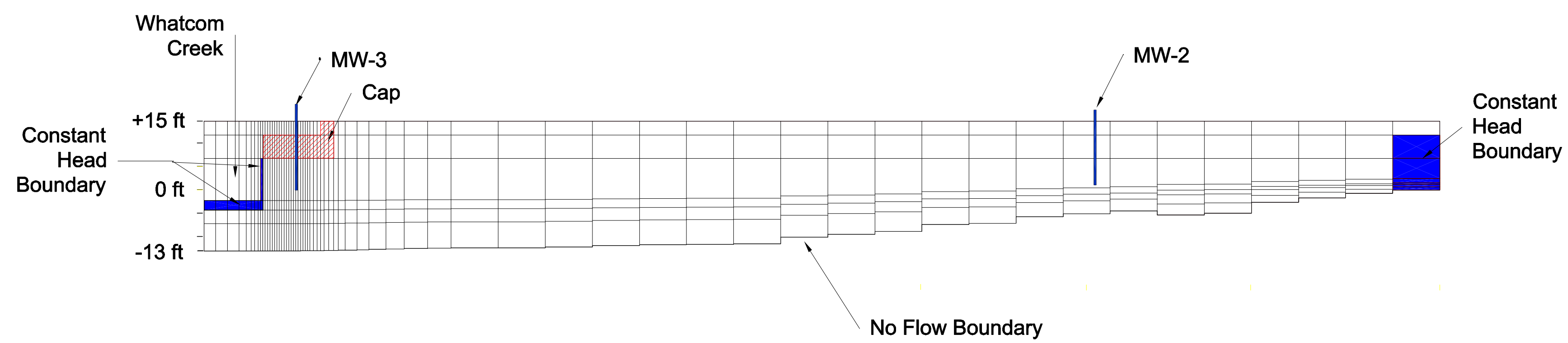
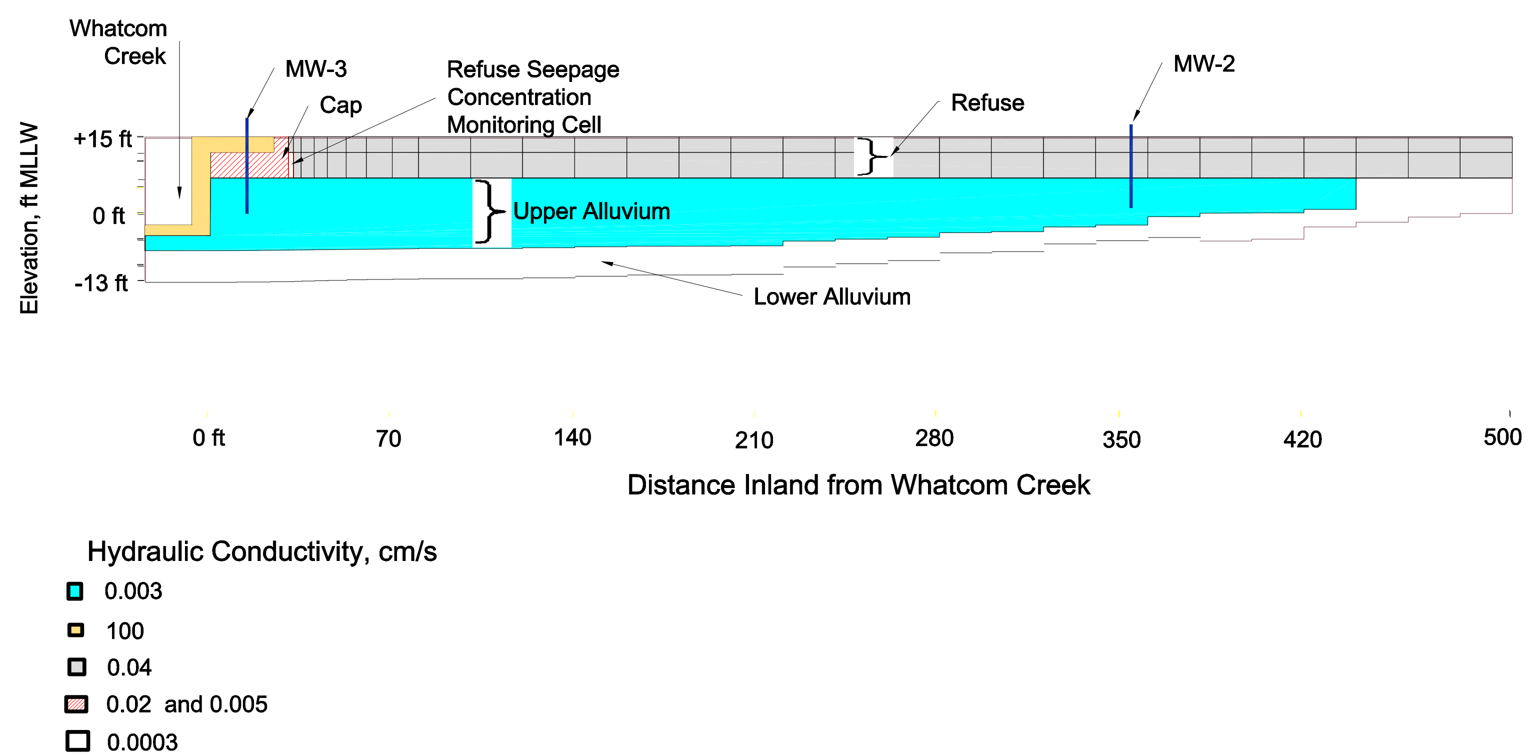
\CALIBRATION.XLS\\FlowCal

Figure C-2 - Flow Model Calibration Results
990139-8

## C-3a - Cap Performance Model Grid with Boundary Conditions




## C-3b - Hydrogeologic Unit Representation





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**Model Layout for Cap Evaluation**

Holly Street Landfill

Bellingham, Washington

| | |
|---|---|
| DATE: 10/03/02 | SCALE: As Shown |
| DESIGNED BY: DWM | PROJECT NO. 990139 |
| DRAWN BY: DWM | FIGURE NO. C-3 |
| REVISED BY: MS | |

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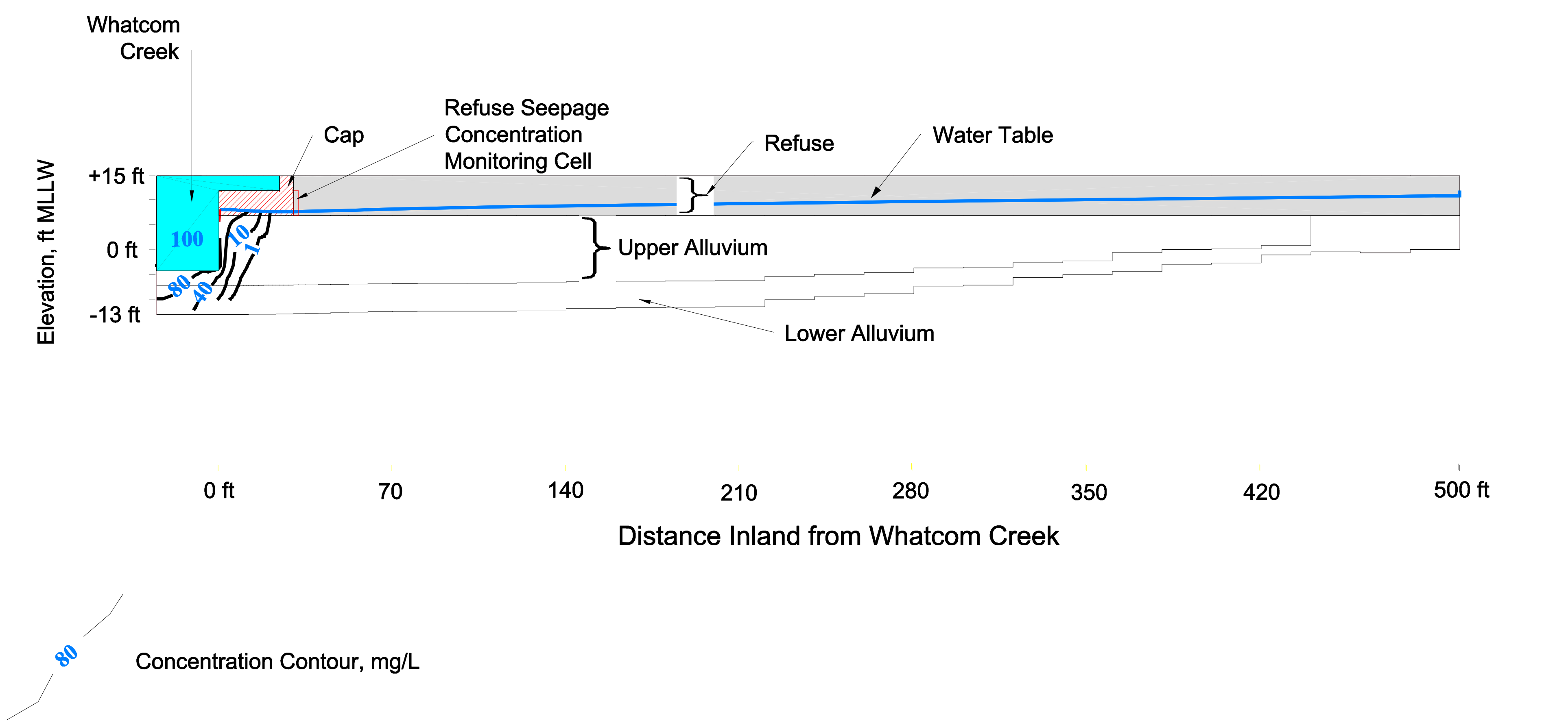


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**Steady-State Concentration**
**Profile for 0.02 cm/s Cap**
Holly Street Landfill
Bellingham, Washington

DATE: 10/03/02
DESIGNED BY: DWM
DRAWN BY: DWM
REVISED BY: MS
SCALE: As Shown
PROJECT NO. 990139
FIGURE NO. **C-4**

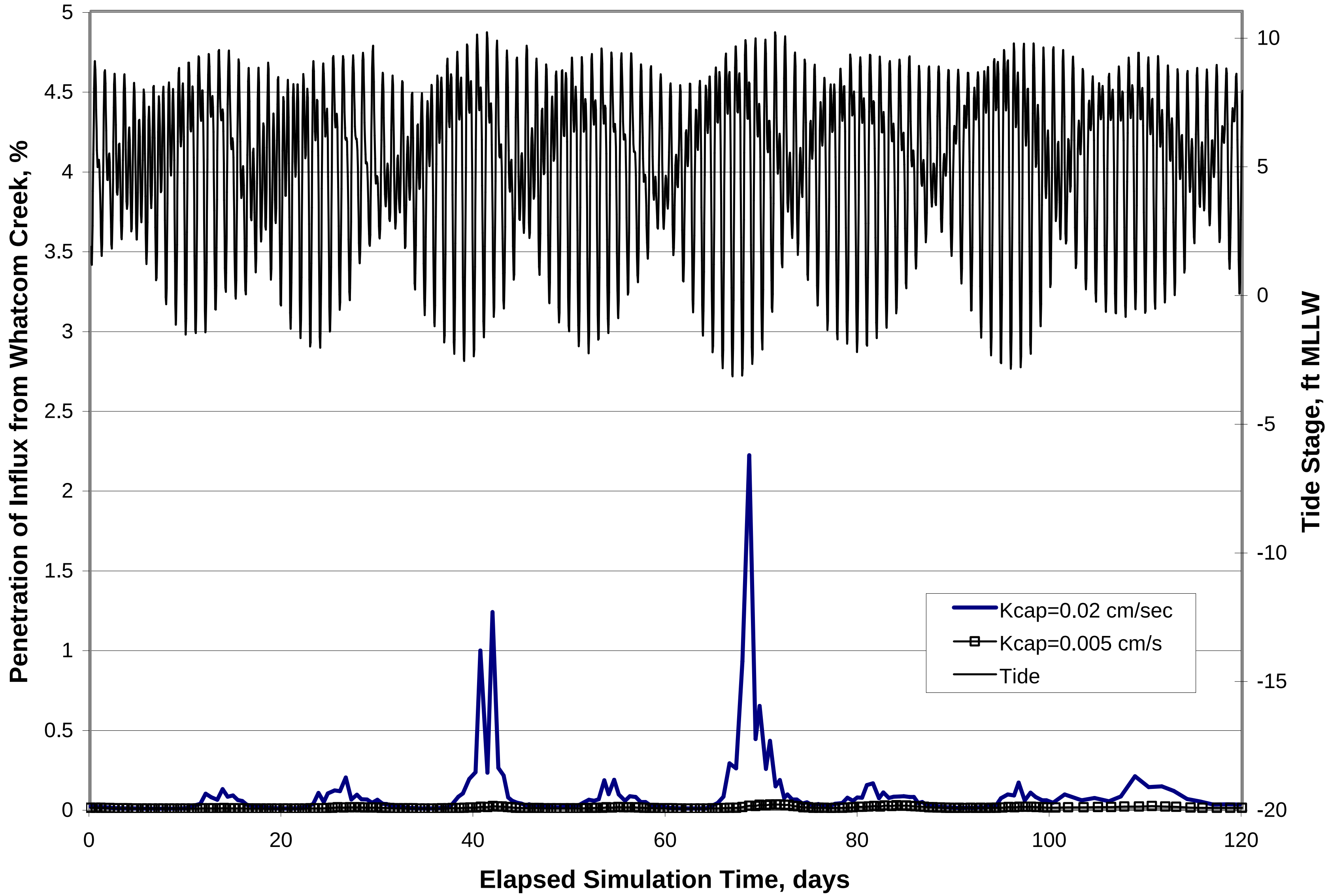


Figure C-5 - Alternative 3 Cap Performance
(Predicted at Face of Refuse)

\June2002ModelingResults.xls\\refuse

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